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HPC Realization of a Controlled Turbulent Jet Using OpenFOAM®

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Introduction

- Zero-net mass flux (ZNMF) actuated incompressible turbulent jets can be studied effectively with DNS simulations at a moderate Reynolds number (Re=2000).
- DNS with OpenFOAM requires excessive number of grid elements because of second order accuracy.
- Two main problems for high fidelity simulations in OpenFOAM:
  1. High time step cost because of solving Pressure-Poisson equation multiple times in pisoFoam:
     → **projectionFoam**
  2. Limited HPC capabilities due to inefficient scaling:
     → **parallel statistical averaging**

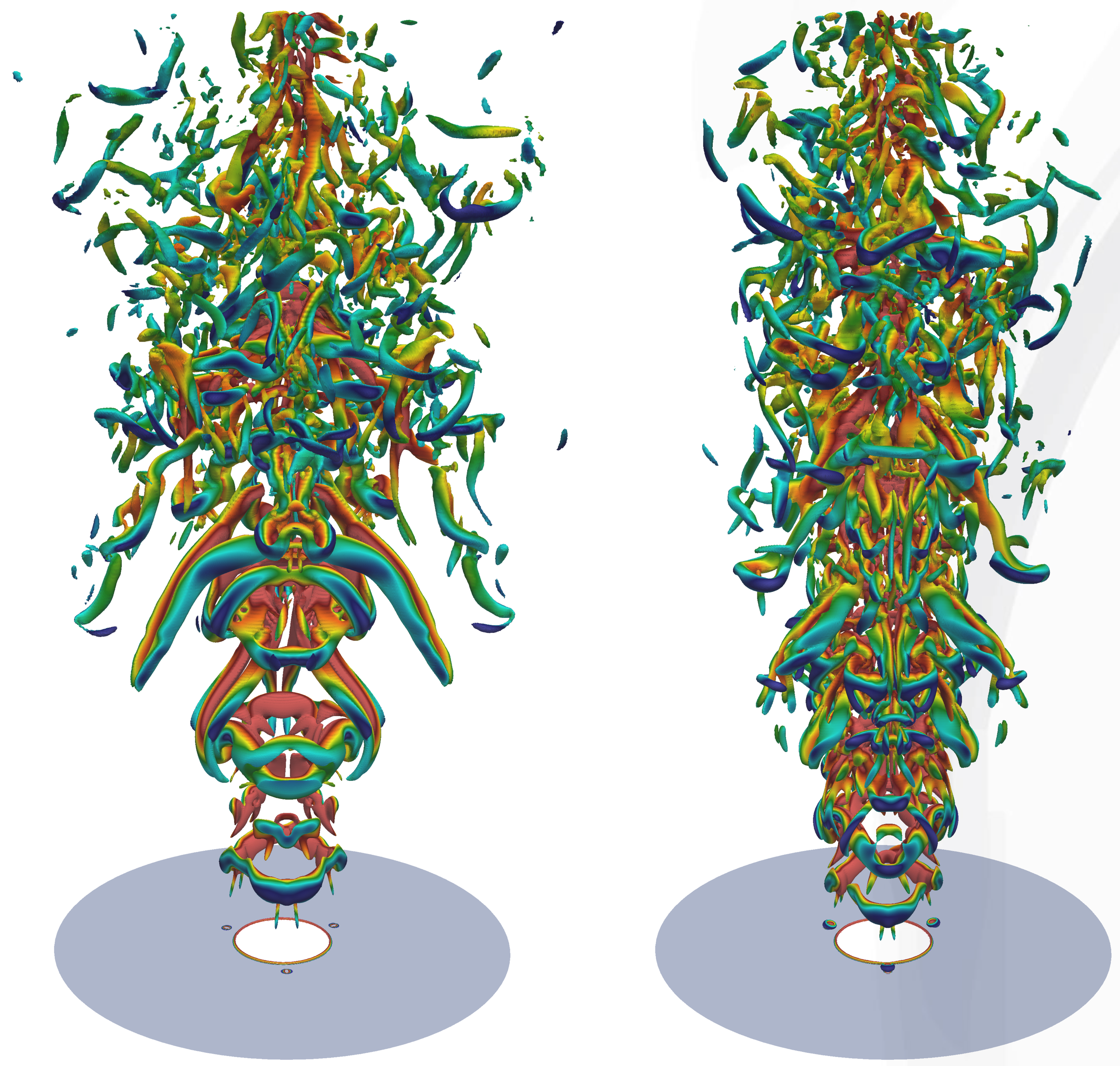

Figure 1: Vortex structures in ZNMF actuated round jets using Q criterion. Actuated with (left): preferred mode frequency; (right): first subharmonic of preferred mode frequency.

Methods

- A new transient solver entitled "**projectionFoam**" is implemented to replace iterative pisoFoam and reduce the time step cost.
- projectionFoam is based on incremental projection scheme[1] which keeps the second order temporal accuracy for velocity.
- Second order extrapolation is employed for convective flux to ensure second order overall accuracy in time.

projectionFoam

1. Second order extrapolation for convective flux:
```
phi_o=0.5*(3.0*phi.oldTime()-phi.oldTime().oldTime());
```
2. Momentum step:
```
fvVectorMatrix UEqn ( fvm::ddt(U)
+ fvm::div(phi_o, U) + turbulence->divDevReff(U));
solve(UEqn == -fvc::grad(p));
```
3. Modification for Rhie-Chow interpolation:
```
U += dt*fvc::grad(p);
```
4. Projection step:
```
fvScalarMatrix pEqn(fvm::laplacian(dt, p) ==fvc::div(phi));
pEqn.solve();
U -= dt*fvc::grad(p);
```

* Full source code is submitted to Unsupported Contributions Repository of the OpenFOAM foundation. Additionally it is available on Ref. 2.

- Parallel scalability performance was found insufficient to do a DNS simulation in a feasible time margin. To overcome this problem we employed **parallel statistical averaging**[3,4]. It is a hybrid concept to calculate statistical moments combining time averaging with ensemble averaging:

$$\langle \boldsymbol{u}(\boldsymbol{x})\rangle \approx \frac{1}{R}\sum_{r=1}^{R}\frac{R}{T_S}\int_{t}^{t_0+T_S/R}\boldsymbol{u}^{\{r\}}(\boldsymbol{x},t)\,\mathrm{d}t$$

- We start R turbulent flow simulations with different initial disturbances to allow statistical independency among them. Once the turbulence is fully developed, we collect statistics in every member of the ensemble.
- Parallel statistical averaging allows additional speed-up by reducing the statistics collection time T_s to T_s/R.

Results

Validation of projectionFoam

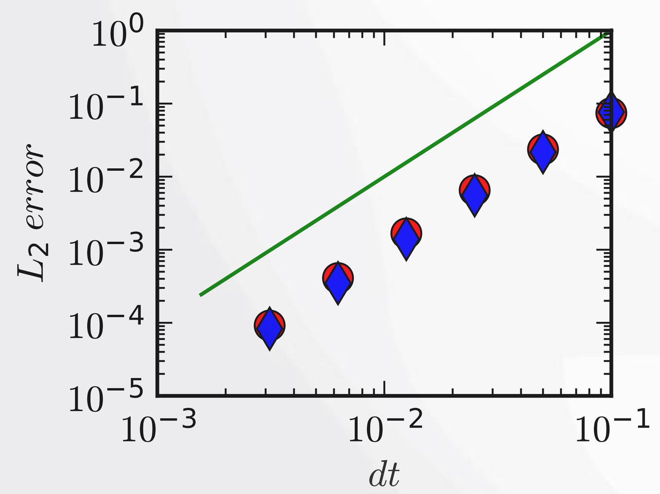

Figure 2: Error for Taylor-Green vortex case using Crank-Nicolson time integration. (●): pisoFoam; (♦): projectionFoam; (—): slope=2

DNS of a controlled jet with 124.117.500 elements

- Parallel performance test on Tier-1 supercomputer of Flemish Supercomputer Center equipped with Intel Sandy Bridge microprocessors and FDR Infiniband Mellanox communication network:

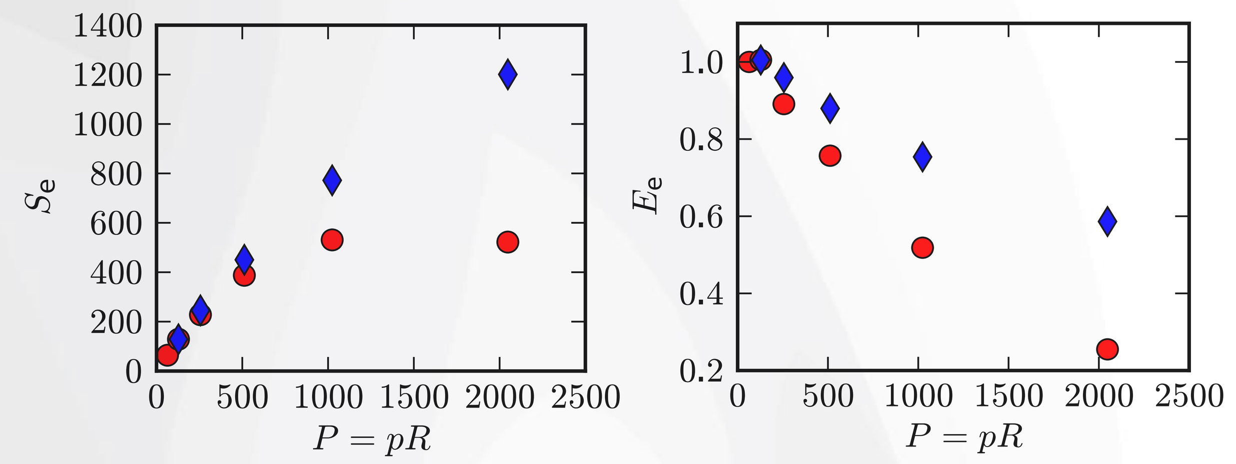

Figure 3: (left): speed-up; (right): parallel efficiency. (●): only domain decomposition; (♦): domain decomposition combined with parallel statistical averaging.

- P=624 processors (p=156, R=4) are employed and speed-up of S_e=540.56 and parallel efficiency of E_e=0.87 are obtained.
- Solver performance on 128 processors:

	execution time	# Poisson solutions
pisoFoam	71.5 s	2
projectionFoam	49.1 s	1

Summary and Conclusion

- projectionFoam allowed a performance gain above 30% over pisoFoam.
- Speed-up and efficiency can be effectively increased by using parallel statistical averaging in combination with domain decomposition parallelism.

References

1. J. van Kan. A second-order accurate pressure correction scheme for viscous incompressible flow. SIAM J. Sci. Stat. Comput., 7(3):870–891, July 1986.
2. https://github.com/asimonder/projectionFoam
3. D. Carati, M. Rogers, and A. Wray. Statistical ensemble of large-eddy simulations. Journal of Fluid Mechanics, 455:195–212, MAR 25 2002
4. A. Onder, P. Wu, and J. Meyers. Improving speed-up and efficiency in simulation of stationary turbulent flows by parallelization of statistical averaging. In Proceedings of the 9th International ERCOFTAC Symposium on Engineering Turbulence Modeling and Measurements (ETMM9), June 2012.

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